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Regular paper

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This work aimed to a study on the application of soft magnetic composite materials in rotor and stator cores of rotating electrical machines. Traditionally, the cores of electrical machines are constructed from laminated steel sheets. The cores developed were obtained by an alternative process of Powder Metallurgy in which iron powder is mixed in different percentages of phenolic resins, compacted and cured. Initially, specimens were prepared to obtain their magnetic and electrical properties, and then simulations were performed using the finite element software FEMM 4.2, considering the topology of a conventional induction motor of 10HP. The simulations were performed considering stator and rotor cores of iron-resin composite material, pure iron sintered and laminated steel sheets for comparative analysis of torque and magnetic flux density of the air gap. The simulated machine constructed by laminated sheets core presented a magnetic flux density 2.02 T and torque 34.49 Nm. The machine by iron cores with 1% resin presented values 2.02 T and 27.10 Nm, respectively. Also were performed tests of these materials in magnetic cores fed with variation of the frequency of electric current, where it was found that, from 500 Hz, the total losses in magnetic cores of composite materials tend to equalize the losses in the laminated sheets core.

Keywords: Soft magnetic materials, powder metallurgy, core of electrical machines, finite element simulation.

1. Introduction

The magnetic cores of rotating electrical machines (stators and rotors), with rare exceptions, are presently built from thin metal foils (sheets of low carbon steel) with thickness less than 1 mm, grouped in packages of sheets. Some machines with better performance, as the generators are constructed from sheets of silicon steel, with a percentage of approximately 3% silicon. The total process for construction these cores consists basically of lamination, stamping, a process for electrical isolation between adjacent sheets, packing and fixation [1].

The rotor and stator cores are surrounded by the field windings and armature respectively, where the field windings are fed by continuous electrical current, and armature windings are powered by alternating electrical current three-phase or polyphase. On some machines the field windings are replaced by permanent magnets, typically NdFeB. Cores surrounded by magnetic coils powered by alternating electrical current, are subject to the action of eddy currents, also known as Foucault currents, which are responsible for considerable loss of power in these cores. The construction of these magnetic cores from steel sheets electrically isolated, partially reduces eddy currents, reducing the losses by Foucault current [1].

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However, using the processes of Powder Metallurgy (P / M) is possible to construct these cores unique solid block with high magnetic permeability (characteristic of magnetic steel) and a high electrical resistivity [3]. In so far as is possible to construct motors in single blocks and solid, fewer steps are present in the construction thereof, and less energy is consumed in the production of machines. It should be noted however, that the conventional electric motors with cores of laminated sheet, as a rule, have significantly higher performance when compared to electric motors with solid cores, even those obtained from the powder metallurgy processes. Thus, the application of powder metallurgy in the cores of electric machines, is restricted to special electric motors where the performance is not the most important criterion, or in some servo motors where the armature windings are fed with electric current of high frequency, reaching up to 600 Hz for example. Another application is in generators with permanent magnets with a large number of poles. In this case, despite the electrical currents involved are high frequency, the rotation of the rotor can occur at low frequencies, since the angular velocity of rotation of a rotor and frequency of the currents are proportional, but this relationship also depends on the number of poles the machine. It is worth noting that from the 400 Hz frequency of electrical current, the magnetic cores obtained from the processes of powder metallurgy, have similar performance to the cores of laminated sheets and may even achieve superior performance [3, 4].

Thus, this work was aimed at the development and testing of composite magnetic materials from iron powder combined with phenolic resin and its application in cores of electrical machines, replacing the traditional packages laminated steel sheets. Initially specimens were obtained, which was used phenolic resin powder in percentages of 1, 3, 5, 8 and 10%, mixed with pure iron, compacted and cured. After, some physical properties were evaluated, such as saturation induction, coercivity and magnetic permeability, electrical resistivity and magnetic losses in function of frequency. Finally, using the finite element software FEMM 4.2, was carried out to simulate an electrical machine with permanent magnet rotor and stator cores from the iron- resin composite, obtaining data of air gap flux and maximum torque.

2. Materials and Methods

2.1 Formulation and characteristics of materials used

The study was conducted from composites, consisting of five iron percentages of phenolic resin. The iron powder used was supplied by Höganäs do Brasil Ltda and the resin powder for SI Crios Group Ltda. Phenolic resin used is a trade name HRJ-10236 Novolac type. The nomenclature follows Fe-HRJxx, where Fe is iron and xx is the percentage by mass of resin of 1.0%, 3.0%, 5.0%, 8.0% and 10%. The iron powder was mixed with different percentages of resin in a double cone mixer, with speed of 60 rpm for 20 minutes for dispersion of the constituents.

2.2 Obtainment of the Specimens

The physical properties of the Fe50%Ni alloy were obtained from the preparation of the obtainment of the physical properties of interest for the materials studied were obtained from specimens with predefined geometry.

The electrical resistivity was determined by measuring the electrical resistance of the specimens in the form of bars and dimensions of theses bars. The resistance was measured by a single electrical multimeter [5, 6]. Figure 1 - (a) shows the die used for compression of the bars, and figure 1 - (b) shows the specimens in the form of bars, where it can be seen that the bars with rounded ends (in the figure above) were milled to a parallelepiped shape with well defined dimensions (in figure below).

Figure 1 – Samples in the form of bars – (a) Die – (b) Specimens

The magnetic properties were determined from specimens in the form of a toroid (Rowlands ring), with the magnetic hysteresis curves tracer, model TLMP-TCH-14 [6]. Figure 2 - (a) shows the die used for compressing the rings, and Figure 2 - (b) shows the specimen obtained.

Figure 2 – Samples in the form of toroids – (a) Die – (b) Specimen

The magnetic losses by eddy current and hysteresis loop were determined from specimens in the form of cores E and T. The cores are wound in typical voltage transformers, with coils of the primary and secondary winding. Applying the nominal voltage and a determined electric current in the primary winding and maintaining open the secondary winding, all the power delivered to the transformer, discounted the power dissipated on cupper of the primary winding, is converted to magnetic losses in the core. Because the analogy among the intrinsic operation of rotating electric machines and transformers voltage, the same tests can be extended to cores of electric motors [6]. The Figures 3 - (a) and 3 - (b) show respectively the dies used for compressing the core E and T, and figure 3 - (c) shows the specimens obtained.

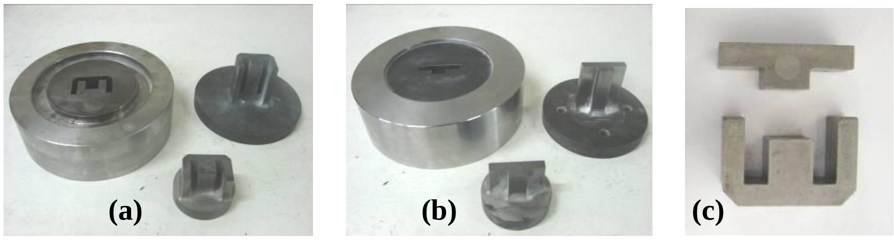


Figure 3 – Samples in the form of transformer core – (a) Core E die – (b) Core T die – (c) Specimens

The process of obtainment of the specimens consisted of a mixture of powders, compaction and curing [7]. Compression is performed in a hydraulic press brand EKA with capacity of 40 tons. Was used compaction pressure of 600 MPa, and 1 Pa = 1 N/m2. Once 1 ton is approximately 10,000 N, results in a pressure of 6 ton / cm2 considering the area of the cavities of the dies [8].

2.3. Procedures for the simulation of synchronous machine with permanent magnets

The magnetic properties were obtained from the specimens in the form of a totoid (Rowland ring), with the magnetic hysteresis curves tracer, model TLMP-TCH-14 [6]. After, added in the FEMM 4.2 software the magnetization curves obtained, in order to enter in the software the magnetic properties of materials with different percentages of phenolic resin [9].

The synchronous machine with permanent magnets simulated in this study was designed based on the structure of an induction motor of 4 poles and 10 hp. The topology and dimensions of the rotor core were based on the classic design of conventional reluctance machines and salient pole synchronous machines [1, 2].

Figure 4 - (a) shows, from a cross-sectional, the dimensional design of the electrical machine. The design of the rotor was carried out taking into account the characteristics of materials processing by powder metallurgy, whose appropriate form must be the least complex possible, thus enabling its construction and also to avoid faults and cracks in the parts constructed [10, 11].

It was used the methodology of winding in series to a 4-pole machine, with 12 turns of wire 12AWG for stator slots. The nominal current used, according to the induction motor used as a reference for the design of the machine, was 14.2 A, for a voltage of 380V (to Y-connection) [1, 2]. In summary, the data for simulation are listed below:

- Current: 14.2 A
- Number of turns per slot: 12
- Wire: 12AWG
- Number of conductors in series per phase: 192
- Packet Size (depth of the stator): 150mm
- Number of slots: 48

- Voltage: 380V (only for traditional machine-rolled sheets. For simulations of the other machines – by composite materials – was considered only the electric current).

The salients and magnets in the rotor produce four poles with polarities reversed in the angular sequence, and the same feature must occur with the magnetic field generated by the armature windings, ie, produce a reversed sequence of four poles on the perimeter of the stator 360 degree. This characteristic of the magnetic field coupling, result in a synchronous electric machine in which the rotor and rotating magnetic field (originated from the armature windings) rotate at the same speed with an angular phase in function of the load of the machine [1, 2]. Figure 4 - (b) illustrates the machine structure to simulate in the finite element software - FEMM 4.2.

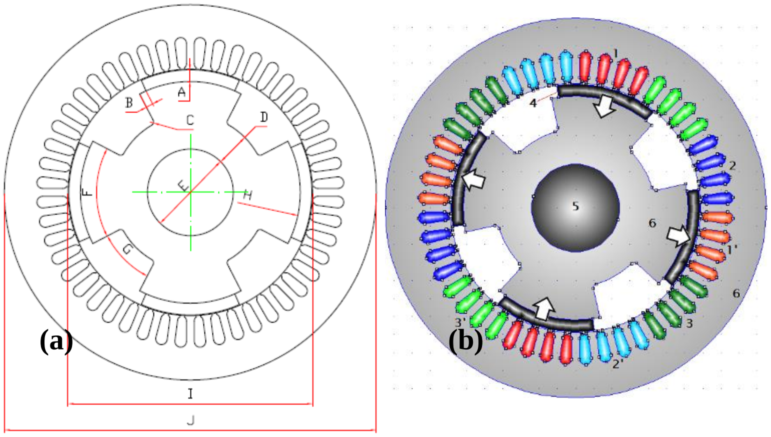


Figure 4 – (a) Coordinates of the rotor in cross-section – A = 6.55; B = 4; C = 2; D = 18.575; E = 49.8; F = 55°; G = 35°; H = 62.05; I = 138; J = 210. (b) Cross section of the machine analyzed in simulation software: 1, 2 e 3 – Poles for current “U”, “V” e “W”, respectively; 1’, 2’ e 3’ – Poles for current “-U”, “-V” e “-W”, respectively; 4 – NdFeB magnets with their respective orientation; 5 – Machine shaft; 6 – Rotor and stator cores

Simulations were performed to stator and rotor cores with low carbon laminated sheets, pure iron sintered cores, and iron-resin composite material cores with different percentages of phenolic resin.

3. ELECTRICAL AND MAGNETIC PROPERTIES OBTAINED

The graph in Figure 5 shows the hysteresis loops of sintered pure iron (Fe Pure) and composite materials with different percentages of phenolic resin:

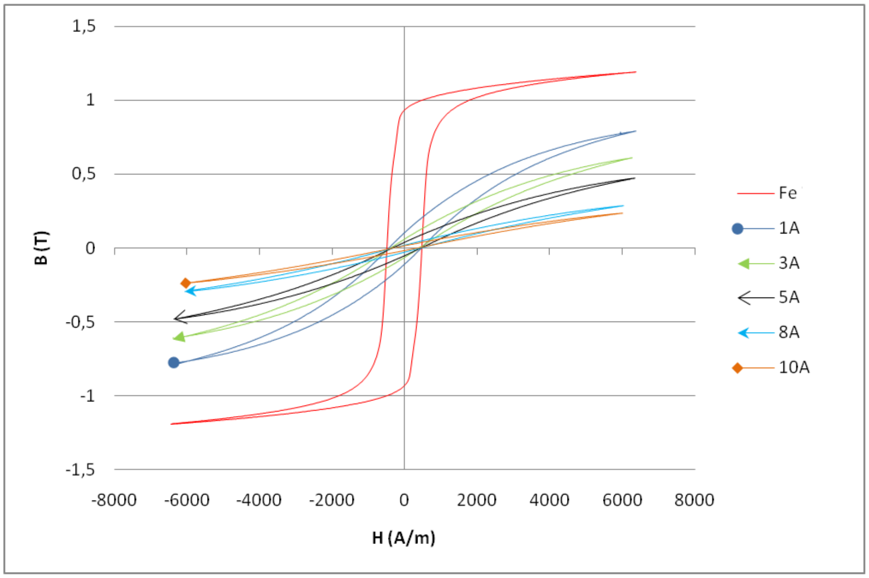


Figure 5 – Hysteresis Loops of the studied materials

From figure 5 it can be seen that the resin composite materials have hysteresis loops different of sintered pure iron (Fe pure). It should be noted that the hysteresis curve of Fe pure, has characteristics similar to low-carbon iron, typical material used in packs of laminated sheets cores used in the construction of conventional rotating electric machine. The maximal induction is less in the resin materials, where the composite with a lower percentage of resin, is that material which present the maximal induction more similar to Fe pure. The low maximal induction indicates that the cores of electric machines constructed from these composites, present less magnetic flow of air gap compared with the Fe pure cores and sheets cores. However, as the hysteresis loop areas of materials with resin are lower when compared to Fe pure and low carbon steel sheets, the losses due to hysteresis loop of these composites are lower [12, 13].

Table 1 shows the results of electrical resistivity, calculated from the geometry and electrical resistance of the bars (Figure 1-b) and the magnetic characteristics obtained from the graphs of Figure 5.

Table 1 – Magnetic and electrical characteristics of the composite FeHRJ and Fe (pure) Sintered

Alloys	ρ (μΩ.m)	B_r (T)	H (A/m)	Hc (Oe)	μr
Fe*	0,14	1,18	127	1,6	3700
Fe-HRJ01	490	0,105	410	5,2	134
Fe-HRJ03	774	0,057	400	5	96
Fe-HRJ05	1665	0,046	390	4,9	70
Fe-HRJ08	-	0,023	345	4,3	47
Fe-HRJ10	-	0,015	310	3,9	33

* Iron pure sintered

where:

Electrical Resistivity, ρ;
Retentivity, Br;
Magnetizing Field, H;
Coercivity, Hc;
Relative Permeability, μr;

Table 1 shows that the greater the percentage of resin in the composite, the greater the resistivity ρ and the lower coercivity Hc, which is desirable for use in cores of rotating electrical machines, since in this way reduces the eddy current and hysteresis loop losses. However, the relative magnetic permeability and saturation induction are low, which is not desirable [12, 13, 14].

Losses in magnetic materials studied were determined from specimens in the form of E and T cores, identical to the cores of transformers of conventional voltage of the same dimensions and same windings. Thus the magnetic losses were determined similarly to losses in a conventional transformer with laminated sheets cores. The winding on side of the high voltage was designed to operate at a voltage of 127 Vrms and the low voltage winding was designed to operate at a voltage of 12 Vrms, whereas the core of conventional sheets. The tests were performed using a source of alternating voltage with varying amplitude and frequency. Was used a frequency range of 50 Hz to 1 kHz. The windings of the side of the low voltage were supplied with a voltage approximate 6 Vrms (half of nominal voltage winding), keeping open the high voltage winding, and was varied the amplitude of the low voltage side until to the high voltage side reach to 75 Vrms. This ensures that the voltage induced in the secondary (high voltage side) remains constant for the cores studied. After measured the power supplied by the source and cashed the losses in the coil. The resulting power is directly related to losses in the core by eddy current and hysteresis loop [15, 16].

Figure 6 shows the graphs of loss in watts for frequencies from 50 Hz to 1 kKz to the transformer with core sheet and to the cores of composite with 1, 3 and 5% HRJ resin. The losses in the cores of composite with 8 and 10% resin could not be determined since the cores are deformed during the curing the resin process. In general the composite with these percentages were discarded for use in electrical machine cores due to the decrease in magnetic properties [12, 13, 14].

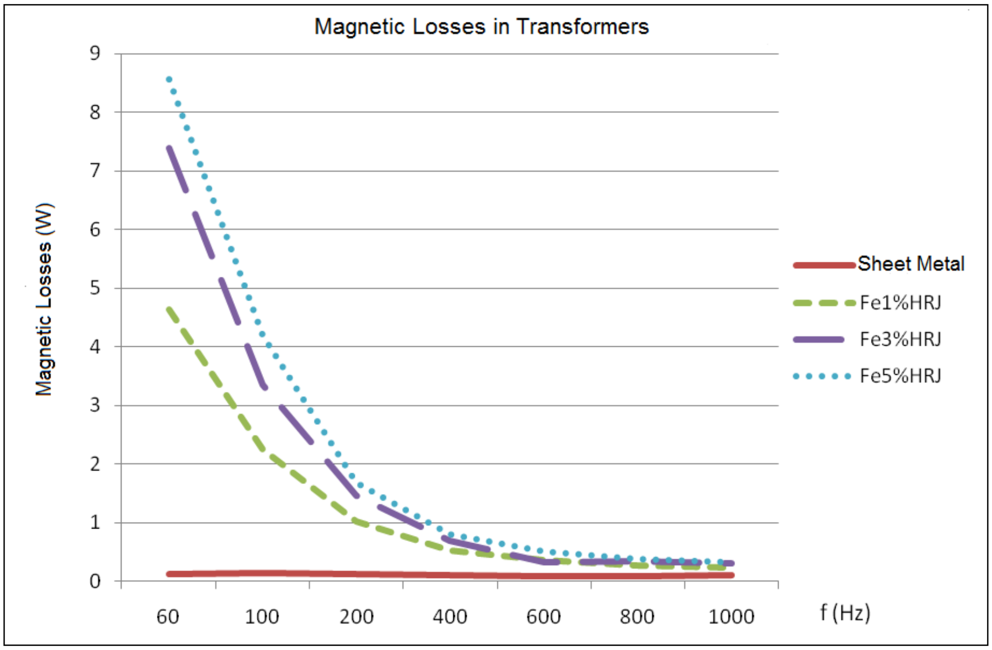
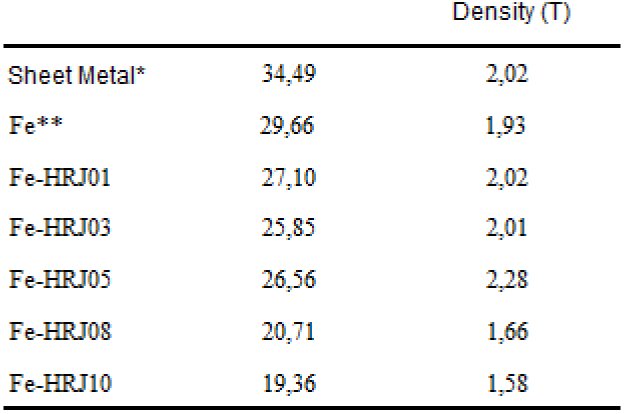


Figure 6 – Magnetic losses in transformers with cores sheets and Fe with 1%, 3% e 5% HRJ-10236 resin

4. ELECTRICAL AND MAGNETIC PROPERTIES OBTAINED

Table 2 shows the torque and the maximum flux density (magnetic flux gap) in the simulations with the laminated steel sheets and the materials obtained by powder metallurgy processes.

Table 2 - Results of Torque and Flux Density Maximum



Material	Torque (N.m)	Maximum Flux Density (T)
Sheet Metal*	34,49	2,02
Fe**	29,66	1,93
Fe-HRJ01	27,10	2,02
Fe-HRJ03	25,85	2,01
Fe-HRJ05	26,56	2,28
Fe-HRJ08	20,71	1,66
Fe-HRJ10	19,36	1,58

* Laminated steel sheets, used commercially in electrical machines.
** Pure iron sintered

In a rotating electric machine, running as a motor or generator, the torque on the shaft is a function of air gap magnetic flux (maximal induction). A rotating electric machine is a dynamic transducer energy, ie as the motor turns electrical energy of the armature windings in mechanical energy delivered to a load on the shaft. In a generator, the reverse takes place, ie, turns mechanical energy on the shaft, from a turbine for example, into electrical energy. In both cases, the conversion of electrical energy to mechanical and vice versa, occurs from the magnetic field, and magnetic flux air gap (or maximal induction) is the determining factor. [1, 2] As a result, through simulation, are considered as best performing machines that operate with higher air-gap magnetic flux and the higher final torque.

Figure 7a shows the lines of magnetic flux for machine with laminated sheets obtained from the software FEMM 4.2. Figure 7b shows the magnetic flux lines for the machine having a core built from the Fe-HRJ01 composites (composites with better magnetic characteristics). The darker regions in the figure show the largest magnetic flux, and this fact is explained because the magnets are in the exact center of the poles of the electric machine.

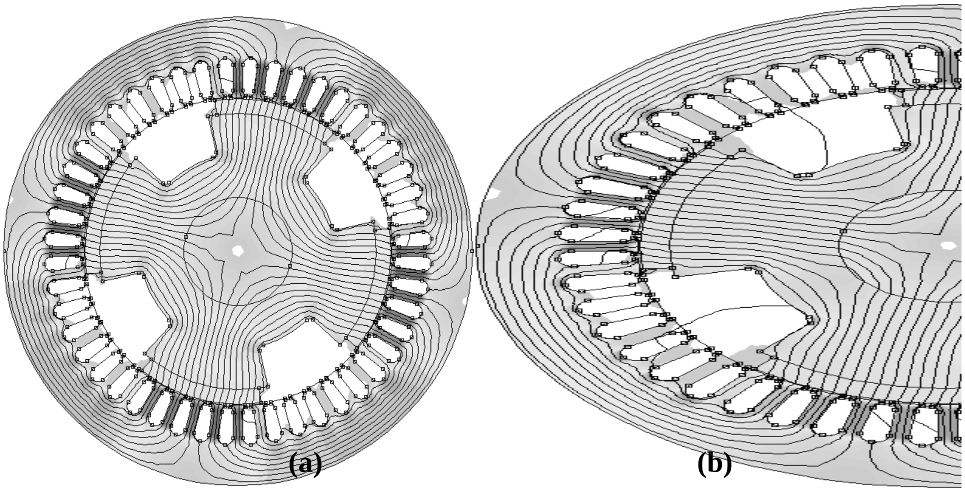


Figure 7 - Flow lines for electric rotating machine simulated: (a) core sheets, (b) core with Fe-HRJ01

From the results of magnetic flux in the machine it was possible to obtain the peak of this phenomenon, inside the machine, [9] as shown in the graph of Figure 8.

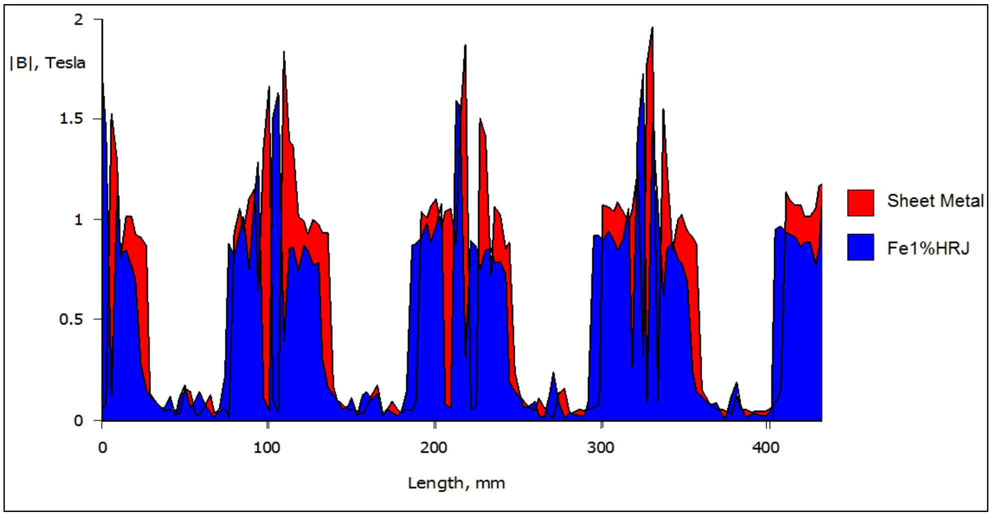


Figure 8 - Peak intensity of magnetic flux in the rotor and stator (sheets and FE1% HRJ composite)

The tests and simulations performed with composite resin showed promising results in comparison with machines built from the conventional method of laminated sheets. The magnetic flux in the core FE1% HRJ showed similar results with respect to traditional laminated steel sheet, but there was a reduction in final torque of the electric machine, whereas the same excitation power. This problem can be solved particularly in applications which have input power with the possibility of varying the voltage applied which can increase the magnetic flux and maintaining the torque at levels similar to traditional machines designs with laminated sheets [11, 12, 13].

The electric machines in use are subjected to loads, which in addition to exerting a resistive torque to do so may result in vibration in the machine-load system. For this reason, the possible materials for use in cores of electrical machines must have the mechanical behavior compatible to the stress needed when the machine is in operation. In this case, the composite materials studied in this work have mechanical stress lower to the levels achieved in laminated steel and sintered iron. [12, 17] The mechanical stresses in an electric machine varies with the weight and speed of the rotor. Typically the rotor is subjected to stress from two sources that are, the rotation and magnetic conjugate (torque) among the stator and rotor fluxes. The stator is subjected the same request of the electromagnetic force of the conjugate, but is not moving. In small engines and low rotation speeds the magnitude of these forces will not be significant. The highest demands in these cases are concentrated in the conditions of the production of the machine (coil windings and montage). Generally, the soft composite material can reach values of 50 to 150 MPa for transverse rupture strength. These values can be improved depending on the techniques used to obtain the finished piece. Thus, studies are being extended to resins which allow higher ductility of parts produced, as some resins that have both thermosetting and thermoplastic behavior and use in temperatures close to 150 oC. Important to note also that the use of composite resin materials in machines operating at high frequencies, necessarily the high frequencies does not refer to the speed of rotation of the rotor, but the electrical currents in the windings of the machine. Thus the limitations of using these composites in cores of electrical machines due to inferior mechanical properties when compared to cores with packages laminated sheets can be circumvented by making special considerations when the machine is designed from composite materials. [4, 12, 13]

4. Conclusions

In comparison with the composite FE1% HRJ, the simulation results of the iron with higher content of resin were lower, possibly due to saturation of the resin material, thereby decreasing its magnetic properties. Mechanically the composites have their behavior governed by the resin, which, besides acting as an insulator between the iron particles is the agent that gives mechanical stability to the material. The part obtained, after the cure, present fragile structure due to not atomic diffusion, which occurs in the sintering (for sintered parts). Materials developed, although some properties not be beneficial, may be applied in specific electric machines, as in motors operating with electric current of high frequency (due to low losses) in servo motors, generators with a high number of poles and mini and micro motors with complex geometry, where the income is not important, being an alternative to current processes for the manufacture of magnetic cores of rotating electric machines. The fragility of the specimens studied is being bypassed from the study of resins composites with more elastic characteristics to support higher temperatures up to approximately 150 °C. Such composites with other resins with thermoplastic and thermosetting characteristics were tested in preliminary studies, having as main drawback so far, the high cost.

Important to note that hysteresis curves were plotted at low frequencies, or nearly level DC. It is worth noting that the torque simulation results in instantaneous values for a given position relative among the alignment of the rotor and stator cores, without considering the frequency of rotation of the rotor or the frequency of electrical current that supply the armature windings. For this reason it was very important for this study, tests of losses in magnetic cores in form of transformer, which present analogous operation to electric motors cores. It can be observed these tests that, from 500 Hz frequency for electric current, keeping constant the voltage induced, the losses in the cores of composite materials studied are about equal to losses in cores of laminated sheets. It is noted that while the losses in cores of sheets remains constant with increasing frequency, the losses in the core of composite material decays exponentially to 400 Hz This very significant feature of cores obtained from the processes of Powder Metallurgy, as sintered or composite resin, allows its use in certain types of rotating electrical machines as some servo motors that are driven by electric currents of frequencies close to or above 400 Hz, and generators with high numbers poles.

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